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Optical Device and Process

Field of the invention

The present invention relates broadly to an optical device comprising a waveguide and a process for fabricating the same.

Background of the invention

In optical waveguides it is often desirable to direct light around bends, for example to reduce the size of devices incorporating optical waveguides. An inherent problem is, however, that due to the refractive index properties of the waveguide and the material surrounding the waveguide, it is likely that light will be diffracted out of bends, in particular tight bends, thereby resulting in what is commonly referred to as bending losses. Such losses can limit the performance of the device.

The directing of light signals in different directions would also be desirable in devices where it is required to confine light to a predetermined path within the waveguide, for example in optical filter or optical resonator structures.

Summary of the Invention

The present invention provides an optical waveguide structure comprising:

- an optical waveguide having a bend and being formed of a photosensitive material; and
- a grating structure arranged to guide light of a predetermined wavelength around the bend in the waveguide, the grating structure comprising UV-induced refractive index variations in the waveguide.

A substantial reduction in bending loss can be achieved by guiding light around the bend with the grating structure.

The present invention allows for angular dispersion to be added to a propagating light signal which can be controlled by the properties of the grating structures.

For example, this can be utilised for dispersion compensation, pulse shirping, or pulse compressing. This is because different wavelengths see a different angular path with respect to the grating structure.

The device may be utilised in complex light manipulation circuits both in the spectral and time domain.

The grating structure may comprise a chirped grating.

The grating structure may be disposed to direct the light in a reflection or in a transmission mode.

Because of an angular dependence of the accepted wavelength in the grating, the device can depend on angular sweep to isolate wavelengths or signals.

The grating structure may comprise a continuous grating. Alternatively, the grating structure may comprise two gratings which mirror each other.

In one embodiment, the grating structure comprises regions of constant refractive index which extent in the propagation direction of the waveguide.

The regions may extend parallel to the propagation direction.

The regions may extend cylindrically parallel to the propagation direction.

The regions may extend ellipsoidally parallel to the propagation direction.

The device may further comprise at least one optical reflector disposed in a direction transverse to the propagation direction to aid in confining the light to the path.

The device may comprise two or more grating structures angularly disposed with respect to each other to guide light around the bend.

Accordingly, different confinement conditions may be realised at different boundaries of the waveguide.

The grating structures may be formed by UV-holography.

The gratings may be chirped gratings.

The gratings may be sampled gratings.

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The device may be a filter, a resonator, or a sensor.

In one embodiment, the device is a sensor further comprising means for measuring an intensity of the light at a predetermined point along the waveguide for determining changes in the intensity due to induced changes in confinement conditions of the sensor.

The changes may be induced by gas molecules entering the waveguide.

The present invention may alternatively be defined as providing a method of adapting a photosensitive waveguide to guide light of a predetermined wavelength around a bend in the waveguide, comprising:

- using UV light to induce refractive index variations in the waveguide such that at least one grating structure is formed, wherein the grating structure is disposed to guide the light around the bend.

Preferred forms of the invention will now be described, by way of example only, with reference to the accompanying drawings, in which:

Brief Description of the Drawings

Figure 1 is a schematic drawing of a device embodying the present invention.

Figure 2 is a schematic drawing of a device embodying the present invention.

Figure 3 is a schematic drawing of a device embodying the present invention.

Figure 4 is a schematic drawing of a device embodying the present invention.

Figure 5 is a schematic drawing of a device embodying the present invention.

Figure 6 illustrates in an isometric view a method of fabricating a grating confined waveguide embodying the present invention.

Figure 7 illustrates in an isometric view another method of fabricating a grating confined waveguide embodying the present invention.

Figure 8 is a schematic drawing in a cross-sectional view illustrating a device embodying the present invention.

Figure 9 is shows a plot of resonant angle against grating period for a grating confined waveguide.

Figure 10 is a schematic drawing in an isometric view illustrating a device embodying the present invention.

Figure 11 is a schematic drawing in a top view illustrating a device embodying the present invention.

Figure 12 is a schematic drawing in a cross-sectional side view illustrating a device embodying the present invention.

Figure 13 is a schematic drawing in an isometric view of a resonator structure embodying the present invention.

Figure 14 is a schematic drawing in an isometric view of a device embodying the present invention.

Detailed Description of the Preferred Embodiments

Turning initially to Fig. 1, there is illustrated schematically a first example embodiment wherein a

waveguide 1, down which light 2 is to be projected, undergoes a tight bend in the desired path. In the vicinity of the tight bend, a grating structure 4 is written. The grating structure 4 effectively has a photonic band gap preventing the effervescent light 2 from leaking out and resulting in higher efficiency in the light coupled to output 5. This results in a substantial reduction in the bending loss as a result of the utilization of the defraction grating 4 which in turn allows for tighter bends to be formed in the waveguide structure. The wavelength of the grating 4 can be tuned so as to match desired frequencies for operation.

Alternatively, as illustrated in Fig. 2, the grating 6 can be written in a reflection mode so as to provide for reflection of desired frequencies along the path 7 with losses 8 for those frequencies not having desired characteristics.

The utilization of the arrangement of Fig. 2 can be extended so as to provide for wavelength division multiplexing capabilities on a waveguide structure. This is illustrated in Fig. 3 wherein initial light can be launched down a waveguide having a number of frequencies $\lambda 1$, $\lambda 2$, $\lambda 3$ coupled out of the waveguide by utilization of corresponding matched Bragg gratings 12, 13, 14 which operate so as to filter out the requisite frequencies.

Fig. 4 illustrates a further arrangement whereby light coupled along waveguide 15 will be coupled to outputs 16, 17 by means of suitably matched Bragg grating 18 having desired periodic characteristics, matched to the desired frequencies for coupling. The surrounding waveguide refractive index regions eg. 19 can be tapered to provide for stronger coupling. Preferably, the splitter arrangement of Fig. 4 has a Bragg grating coupled such that 50% of the light traverses along each of path 17, 18. This can be achieved for wavelengths twice the Bragg period. Of course, it is possible to adjust the Bragg period to adjust the output angle and coupling efficiency.

Similarly, in Fig. 5 a Bragg grating 20 is provided for coupling around a bend for light travelling along the path 21, 22.

In Figure 6, a waveguide 110 in the form of a layer of photosensitive material has been deposited onto a substrate 112, eg. a silicon wafer having a native oxide layer for optical isolation of the waveguide material 110.

A UV beam 116 from a UV source 114 is focussed (through optical elements 118) in the plane of the waveguide 110. The substrate 112 can be laterally moved as indicated by arrows 120 and 122 to effect writing of planes indicated by lines 124 of a first grating 126 of a grating structure 127, through UV-induced changes of the refractive index of the waveguide 110.

After completion of the first grating 126, a second grating 128 of the grating structure 127 is written by appropriate moving of the substrate 112.

Light of a predetermined wavelength entering the waveguide 110 at predetermined angles of incidence on the gratings 126, 128 are confined to a path extending in the propagation direction 130 in the plane of the waveguide 110. The propagation characteristics of the waveguide 10 will therefore depend on the wavelength of a light signal 131 and an angle θ under which it enters the waveguide 110.

It is noted here, that in the planar structure described above the grating confinement is limited to one-dimension in the plane of the waveguide 110. However, it will be appreciated that waveguides can be produced in a photosensitive waveguide material that are grating confined in two or three dimensions.

For example, as illustrated in Figure 7, holographic UV grating writing techniques using a phase mask 140 can be used to produce a waveguide 142 (propagation direction as indicated by arrow 141) within a block 144 of

photosensitive waveguide material which is grating confined in two dimensions through gratings 146, 148 of a first grating structure 147 and gratings 150, 152 of a second grating structure 151 respectively.

It is noted that the one or more of the grating structures of a device could alternatively comprise a continuos grating whilst still effecting confinement of light of a predetermined wavelength entering at a predetermined angle of incidence on the grating structure.

E.g. the resonator 250 shown in Figure 14 comprises two continuos grating structures 252, and 254 to effect channelling of light 256 of a predetermined wavelength entering the resonator 250 at a predetermined angle of incidence on the grating structures 252 and 254 around a ring path 258.

Grating confinement can also be achieved in an optical fibre, e.g. using a cylindrical grating structure 320 around a guiding core 322 (propagation direction perpendicular to the drawing plane) of an optical fibre 324 as illustrated in Figure 12. The grating structure 320 effects confinement to a path extending in the propagation direction of light of a predetermined wavelength entering at a predetermined angle of incidence on the grating structure 320.

It will be appreciated by a person skilled in the art that for a non-cylindrical grating structure confinement conditions can vary in different radial directions.

The underlying principle of grating confined waveguide propagation is the Bragg condition. For a ray travelling in a medium of index n, peak reflectivity occurs when the wavelength λ satisfies:

$$\lambda = 2n\Lambda\theta / m \qquad (1)$$

where m is the diffraction order of the grating and θ is the angle of the ray with respect to a single groove of the grating. This single equation contains within it the

entire properties of grating confinement such as e.g. so-called photonic crystal fibres.

Figure 8 shows the plot of resonant angle against grating period for the wavelength regime 1200-1600 nm for 1st, 2nd and 3rd order grating diffraction. At longer periods, variations in the resonant angle converge to within a few degrees, although the effect is largest for the 1st order. The physical interpretation is that for a large number of wavelengths the incident angle is approximately the same equating with similar diffraction properties. Therefore grating confinement will occur over a large bandwidth for a small input coupling angle at longer periods under identical launch conditions. Outside this regime radiation loss will occur.

Other interesting properties are noted. There exist other regimes of incident angle at which total internal reflection can occur to enable propagation along the grating confined waveguide. Light coupled into higher diffraction orders at much larger incident angles can also satisfy the Bragg relation, giving rise to higher order bandgaps. The effective coupling strength is reduced for higher order mode propagation in these regimes and is therefore characterised by larger mode areas. Since the effective index is different, it is possible to have fundamental-like mode behaviour simultaneously with different propagation properties. Thus e.g. photonic fibres have interesting launch regimes which are unlike conventional effective index fibres. These regimes exist because there are angular photonic bandgaps at which light cannot propagate through the surrounding grating cladding. Further, these bandgaps are robust and do not change much in angular properties with increasing period and will therefore be relatively insensitive to bend loss at longer periods.

The angular photonic bandgap is described by the angular reflectivity of the grating. This reflectivity bandwidth can be extremely small, depending upon the dimensions of the grating, its coupling coefficient, and the angle of incidence. For either normal (incident angle, $\theta = 90°$) or angled incidence, the power reflectivity is given from coupled mode theory as

$$R = \left| \frac{K \sinh SL}{S \cosh SL + i\Delta\beta \sinh SL} \right|^2 \qquad (2)$$

where

$$S \equiv \sqrt{K^2 = (\Delta\beta)^2} \qquad (3)$$

K is the angle-dependent coupling coefficient for the grating, L is the length of the grating and $\Delta\beta$ is the detuning of the wavevector, defined by

$$\Delta\beta = \frac{m\pi}{\Lambda} - \frac{2\pi n}{\lambda} \sin\theta \qquad (4)$$

Peak reflectivity occurs for $\Delta\theta = 0$ and declines as $\Delta\theta$ exceeds the magnitude of K. It is readily shown in grating confined waveguides that the angular acceptance of the reflectivity narrows considerably, with deviation away from near normal incidence (as indicated by the decreasing slope of Figure 8). Consequently, the higher order photonic bandgaps will be broader and less spatially selective and this may have implications for the robustness of singlemode operation for large input angles. The variation of detuning $\delta(\Delta\beta)$ with angle $\delta\theta$ is easily calculated from above:

$$\frac{\delta(\Delta\beta)}{\delta\theta} \approx -\frac{2\pi n}{\lambda} \cos\theta \qquad (5)$$

From this sensitivity to the capture angle it is possible to vary the angular dispersion significantly by appropriate selection of the period. Since the angle of incidents are similar at longer periods (Figure 8) the

propagation constants, and therefore the sensitivity to capture angle, tend to converge with increasing grating period - it is therefore possible to achieve a dispersion flattened profile of the type found numerically.

Note that even for light guided solely under the effective index picture when the core index is higher than the surrounding cladding, unless the mode vector has an angle resonant with that of the grating, light can quickly couple to radiation modes and leak out. Further, this intolerance to the mode angle gives rise to the high spatial selectivity of these angular bandgaps such that single-moded propagation is robust especially for long grating periods. The mode profiles that are supported will therefore resemble the geometric positioning of the gratings radially around the core region and should differ from conventional waveguide guidance where such strict restrictions do not exist.

By recognising the importance of diffraction in a periodic lattice it is easily shown that grating confined propagation is readily achieved in so-called photonic crystal fibres. Further, the associated angular photonic bandgaps are responsible for a range of phenomena that distinguish these fibres from conventional effective index fibres. Extending the applications to resonators made up of these fibres, very interesting behaviour is predicted to occur as a result of the strict vector angles of the propagating modes, including ring-like resonances when the end reflectors are tilted. The polarisation properties of such structures may also differ to conventional resonators and an entire new class of passive and active filters and resonators are possible.

In Figure 9, a resonator 181 can be utilised for WDM (wavelength division multiplexing) filtering if the grating periods (which may be chirped) of gratings 182 and 184 of a first grating structure 183 and of gratings 186 and 188 of

a second grating structure 187 are carefully selected such that a ring resonance is different for different wavelengths and therefore the outputs are spatially at different points. This is schematically illustrated by paths 190, 192 and example outputs 194, 196. The grating structures 183 and/or 187 may be sampled grating structures.

Complex design with the use of sampled profiles etc. can be used to achieve WDM operation. In particular the angular dependence means that it may be possible to get much more closely spaced peaks with higher contrast than conventional normal incidence. It is noted that this is also applicable to fibre (e.g. photonic crystal fibres) geometries.

As illustrated in Figure 10, in a resonator laser design 300 a photonic crystal fibre 302 is located in line in a ring laser 304 (of any sort) to improve both linewidth, laser stability and mode selectivity (including transverse if multi-mode active fibre is used to increase power). It is noted that a similar design can be applicable to linear lasers (of any sort).

As illustrated in Figure 11, in an alternative embodiment, a helical ring fibre laser 310 comprises an optical fibre 312 having a grating confined core structure 314 and spaced apart concave reflectors 315, 316 within the core structure 314. The helical ring fibre laser 310 can thus provide a circularly birefringent output (as indicated by arrow 311).

Furthermore, high power fibre lasers may be provided without using cladding pump configuration. For such lasers, single mode operation and good stability are possible, as well as large mode areas. In such embodiments, the modes are grating diffraction dependent unlike conventional fibres which are aperture diffraction dependent.

It will be appreciated by a person skilled in the art that numerous variations and/or modifications may be made to the present invention as shown in the specific embodiments without departing from the spirit or scope of the invention as broadly described. The present embodiments are, therefore, to be considered in all respects to be illustrative and not restrictive.